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OPTICAL MEASURING APPARATUS OF FILM THICKNESS

Patent Number: JP1054207
Publication date: 1989-03-01
Inventor(s): UCHIDA SHINJI; others: 02
Applicant(s): MATSUSHITA ELECTRIC IND CO LTD
Requested Patent: JP1054207
Application Number: JP19870212186 19870825
Priority Number(s):
IPC Classification: G01B11/06
EC Classification:
Equivalents:

Abstract

PURPOSE:To make it possible to easily obtain positional information of a luminous flux even without removing a light quantity detector, by providing a position detector of the luminous flux separately from the light quantity detector.
CONSTITUTION:The configuration of a luminous flux X2 in a position detector 9 is based on that when a luminous flux X1 is adjusted by a first mirror 5, and adjusting screw 12 and a second mirror 6 to be incident in the central position of a light quantity detector 4. Therefore, only if the position of the luminous flux is adjusted after removing the light quantity detector 4 from a light shield member 1, the position of the luminous flux can be detected, with the position detector 9 mounted. As described above, the position of the luminous flux is detected by the position detector 9, and both the noises and the light quantity level at that time can be adjusted and confirmed simultaneously by the light quantity detector 4.

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㊹発明の名称　光学的膜厚測定装置

㉑特　願　昭62-212186
㉒出　願　昭62(1987)8月25日

特許法第30条第1項適用　昭和62年5月20～5月23日に東京国際見本市会場において開催された「第64回ビジネスショウ」に出品し発表

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明　細　書

1. 発明の名称

光学的膜厚測定装置

2. 特許請求の範囲

1. 複数個のモニター基板と、前記モニター基板を保持するハウジングと、前記ハウジングを順次所定位置に搬送する搬送部と、前記ハウジングに保持されたモニター基板に光束を照射する光束供給部と、モニター基板から反射した光束の光量を検出する光量検出部と、モニター基板から反射した光束が前記光量検出部に入射するよう調整を行うハウジング傾き調整部と、モニター基板から反射した光束を前記光量検出部とモニター基板との間で分離する光束分離手段と、前記分離した光束の位置を検出する位置検出手段とを備えた光学的膜厚測定装置。

3. 発明の詳細な説明

産業上の利用分野

本発明は、光学薄膜を形成する際の光学的膜厚測定装置に関するものである。

従来の技術

レーザ光学、ビデオディスク、光通信、テレビジョン撮像などの電子工学のあらゆる分野で、その発展とともに光学薄膜の開発が盛んになつている。光学薄膜は高い屈折率を有する誘電体物質と低い屈折率を有する誘電体物質を光の波長、あるいはその波長の数分の一程度の厚さに交互に積層して光の干渉を利用して光の反射率、透過率を任意に制御できるようにしたものである。これらの光学薄膜の光学特性は主に屈折率と光学的膜厚で決まるため、膜厚制御のための光学的膜厚の測定技術が重要である。膜厚の測定方法には、例えば水晶振動子の発振周波数変化の測定、膜の電気抵抗の測定などの電気的方法、またはマイクロバランスによる基板に付着した粒子の質量を測定する機械的方法、あるいは干渉色の肉眼による観察、反射率または透過率の測定、偏光の測定ならびに干渉測定などの光学的方法などが考えられている。これらの方法はそれぞれ特徴をもつており、膜の種類、用途に応じて最も適当な方法が用いられて

いる。しかし光学薄膜の膜厚制御のための光学的膜厚の測定という面で考えると、反射率または透過率の変化によつて測定する光学的方法が簡単でかつ一般的である。

従来の光学的膜厚測定装置を第3図を用いて説明する。第3図において、横方向に延びる遮光体21の一端側に設けた光源22より出た光束Xは遮光体21の中央の第1ミラー23によつて反射されて開口部24から出射され、ハウジング25に保持されたモニター基板26に照射される。モニター基板26より反射された光束Xは遮光体21の中央のもう一つの第2ミラー27によつて反射され、遮光体21の他端側に設けた波長選択フィルター28を透過して光量検出器29に到達する。

モニター基板26の下面に薄膜が形成されると、光学的な干渉効果により、光束Xの反射光量が増減するので、この増減量を光量検出器29によつて検出することにより、モニター基板26の下面に成膜された薄膜の光学的膜厚を測定し、制御できる。

次に、上記光学的膜厚測定装置における光束系路の調整方法を簡単に述べる。まず、モニター基板26の中心部に光束Xが入射するように第1ミラー23の傾きを調整する。次にモニター基板26より反射した光束Xが第2ミラー27の中心部にくるようにハウジング25の搬送台30に設けた調整ねじ31を調整し、さらに、第2ミラー27の反射光束Xが光量検出器29の中心部に入射するように第2ミラー27の傾きを調整する。光量検出器29の中心部に光束Xが入射したかどうかの確認は、光量検出器29を取りはずし、代りに磨りガラスなどをいれることにより、光束Xの形状を写し出して行われる。

一般に、モニター基板26は搬送台30上に載置したハウジング25に保持されて、複数個設置されており、以上の手順をすべてのモニター基板26について行つて光学系路の調整は完了する。

発明が解決しようとする問題点

前記光学的膜厚測定装置を用いて、光学薄膜の光学的膜厚コントロールを行うわけであるが、光学薄膜の光学特性向上の1つの課題として前記測定精度が考えられる。測定精度を劣化させる1つの要因として、検出する光束Xの位置のばらつきがある。これは、モニター基板26が何らかの要因で傾いたために、光量検出器29での光束の位置が最適位置より離れて光量不足、光量変化、ノイズなどによる光量劣化が生ずることによる。たとえば、モニター基板26が約0.2度傾いた場合にはモニター基板26から光量検出器29までの光路長が1mとすると、反射した光束の光量検出器29でのずれ量は約14mm発生する。そこで、このずれ量をなくすために、各モニター基板26の傾き調整は敏重に行われる。

モニター基板26の傾きは、基板自身の平行度のばらつき、ハウジング25とモニター基板26との設定のばらつき、ハウジング25のモニター基板取付け部の平行度のばらつき、ハウジング25と搬送台30との設置のばらつき、搬送台30の反りなどが考えられ、またそれらの熱的不安定度なども原因となる。したがつて、調整は薄膜形成準備時間に、毎回各モニター基板26にわたつて十分に行わなければならない。

このように調整は、光量検出器29を遮光体21からはずし、磨りガラスなどを用いて光束形状を観察しながら行われる。一般に、光学薄膜は多層のものが主流で、多いものだと30～90層にもなる。また光学多層薄膜の成膜時間も短いもので3時間普通で6時間程度かかるものであるから、製作時間を短縮する上で上記調整時間を改善することは非常に有用である。

また、光束形状を目視観測して調整を行なつたとしても、実際に光量検出器29を接続してみると、ノイズが多くて高精度な光学的膜厚測定ができないことがある。また、光束位置調整を光量検出器29からの出力情報だけで行うことも考えられるが、効率性、確実性の点から良好な方法ではない。

本発明は上記問題点を解決するもので、光量検出器に到達する光束の位置調整を容易にかつ確実にできて、膜厚コントロールを容易にできる光学的膜厚測定装置を提供することを目的とするものである。

問題点を解決するための手段

上記問題点を解決するために本発明は、複数個のモニター基板と、前記モニター基板を保持するハウジングと、前記ハウジングを順次所定位置に搬送する搬送部と、前記ハウジングに保持されたモニター基板に光束を照射する光束供給部と、モニター基板から反射した光束の光量を検出する光量検出部と、モニター基板から反射した光束が前記光量検出部に入射するよう調整を行うハウジング傾き調整部と、モニター基板から反射した光束を前記光量検出部とモニター基板との間で分離する光束分離手段と、前記分離した光束の位置を検出する位置検出手段とを備えたものである。

作用

上記構成により、位置検出手段において、位置情報を常時かつ即時に得られ、また同時に光量検出器からの光量レベル、光量ノイズを確認しながら光束位置調整が迅速に行えるものであり、これにより、従来のように光量検出器をいちいち取り外すことなく、光束位置調整が正確に行え、高精度な光学的膜厚測定による膜厚コントロールが容易になり、非常に有用である。

実施例

以下、本発明の実施例を図面に基づいて説明する。

第1図は本発明の一実施例を示す光学的膜厚測定装置の概略図である。1は横方向に延びて中央下面に開口部1aを有する箱状の遮光体で、この遮光体1には、一端側に光束供給部としての光源2が、他端側に波長選択フィルター3および光量検出器4が配設されており、また、開口部1aに対応する中央位置には光源2に対向して角度調整可能の第1ミラー5と波長選択フィルター3および光量検出器4に対向して角度調整可能の第2ミラー6とが配設されている。さらに、波長選択フィルター3と第2ミラー6との間には光束Xを2方向に分離する光束分離手段としてのビームスプリッター7が配設され、このビームスプリッター7の光束Xと垂直な上方位置には第2図に示すような磨りガラス8が設けられた位置検出器9が配設されている。また、遮光体1の開口部1aに対向する下方位置には搬送台11に複数のハウジング13が調整ねじ12を介して取付けられ、ハウジング13には底部にモニター基板14が設けられており、搬送台11の移動に伴つてこれらモニター基板14に順次光束Xが照射されるようになつている。

次に、この光学的膜厚測定装置の作用および光束経路の調整方法について説明する。

光源2から出射した光束Xは第1ミラー5によつて反射され、モニター基板14に到達する。第1ミラー5はモニター基板14の中心部に光束Xが入射するように調整される。光束Xはモニター基板14で反射されて、第2ミラー6に到達する。このとき、光束Xを第2ミラー6の中心部に入射させるには、搬送台11に取付けた調整ねじ12によりハウジング13の傾きを調節することにより行われる。第2ミラー6からの反射光束Xはビームスプリッター7に到達し、これを通過する光束X_1と反射する光束X_2とに分離される。ビームスプリッター7を通過した光束X_1は波長選択フィルター3を通過して光量検出器4に入射する。第2ミラー6の傾きは光束X_1が光量検出器4の中央部に入射するように調整される。また、ビームスプリッター7で反射された光束X_2は位置検出器9の中央部に入射するように調整される。位置検出器9は第2図に示すような構造で、光束X_2を磨りガラス8に照射することにより目視観察が可能である。なお、第2図では磨りガラスを用いたが、光束形状を写しだすものなら何でもかまわない。

位置検出器9における光束X_2の光束形状については、第1ミラー5、調整ねじ12、第2ミラー6により光束X_1が光量検出器4の中心位置に入射するように調整した際の光束形状を基準として用いればよい。したがつて光量検出器4を遮光体1よりはずして光束位置調整を行いさえすれば、後は位置検出器9を取付けて光束位置の検出を行えばよいのである。このように、光束位置は位置検出器9を用いて検出し、またその時のノイズ、光量レベルは同時に光量検出器4を用いて調整確認することができる。

一般に、光量不足、ノイズの増大はモニター基板14と、ハウジング13との設置不良が最も多く、この設置不良は光学薄膜の光学的膜厚コントロールに重大な影響を与える。仮に30層もの多層膜を考えてみても、わずか1層の膜厚コントロールを失敗しただけで、光学特性は致命的に悪くなる。したがつて、光学薄膜製造担当者は、モニター基板14の位置設定には特に注意を払うのであるが、前記光学的膜厚測定装置を使用すれば、モニター基板14とハウジング13との設置不良が容易かつ迅速に確認、調整が可能となる。

このように、一度光量検出器4を取りはずして、光学系の調整を行なつてやれば、毎回そのような作業を行わなくても、光束位置調整、光量レベル、ノイズレベルの調整をいたつて簡単に行えて光学的膜厚の測定が容易となり、膜厚コントロールの作業能率の改善、歩留まりの向上が図られ、きわめて有用である。

また、薄膜製造担当者の不注意などでモニター基板14をハウジング13に設置するのを忘れた場合でも前記光学的膜厚測定装置を用いれば、即時に原因を究明でき、きわめて有用である。

また、薄膜成膜時において成膜条件によつて調整ねじ12を使用して光束位置調整ができない場合でも、位置検出器9で検出される光束位置を観測しながら、第1および第2ミラー5，6を用いて調整することができる。

発明の効果

以上のように本発明によれば、光束の位置検出器を光量検出器とは別に設ける構造にしているため、光束の位置情報を光量検出器を取りはずさなくても容易に得ることができるだけでなく、同時に、光束の光量レベル、ノイズレベルを光量検出器で確認調整できるため、その実用的価値はきわめて高く、膜厚コントロールの作業能率の改善や歩留まりの向上などが図られる。

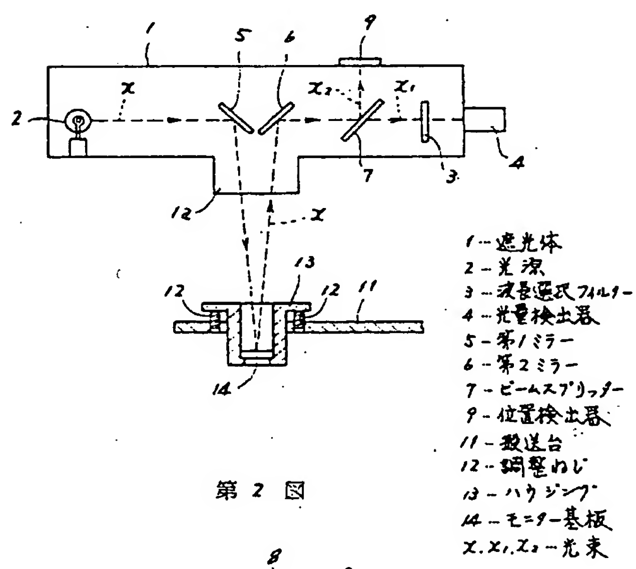
4. 図面の簡単な説明

第1図は本発明の一実施例を示す光学的膜厚測定装置の概略図、第2図は同光学的膜厚測定装置の位置検出器の拡大図、第3図は従来の光学的膜厚測定装置の概略図である。

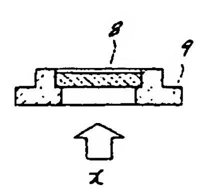
1…遮光体、2…光源、3…波長選択フイルター、4…光量検出器、5…第1ミラー、6…第2ミラー、7…ビームスプリツター、9…位置検出器、11…搬送台、12…調整ねじ、13…ハウジング、14…モニター基板、X，X_1，X_2…光束。

代理人　森本義弘

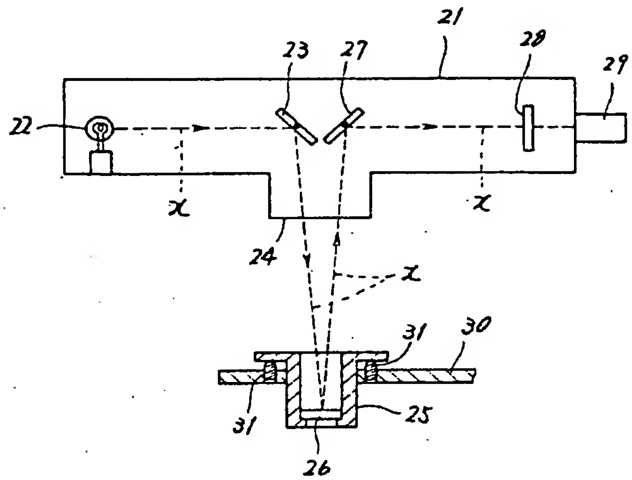
第1図



第2図



第3図



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Invited Paper

Seeing the forest for the trees: a new approach to CD control

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Abstract

Critical dimension (CD) control in advanced semiconductor manufacturing has driven the in-line implementation of complex, high-resolution metrology systems to monitor minimum product dimensions. Yet the high-resolution approach is inconsistent with in-line CD control objectives: resolution does not translate to precision or accuracy, weak response to process parameters inhibits feedback control, sparse sampling precludes partitioning contributors to CD variation, and extendability to future product generations is in question.

We show that superior, affordable and extendable CD control is achieved by optical critical dimension (OCD) measurement of pattern arrays ("forests") whose individual features ("trees") need not be resolved by the metrology tool. The array dimension, averaged over multiple features, responds to CD change about a target value calibrated to the desired device dimension. Response sensitivity greater than that of the minimum dimension can improve the signal-to-noise for feedback control as well as the precision-to-tolerance for product dispositioning. Relatively low-cost and high-speed metrology enables increased product sampling. We describe our application of OCD metrology to 0.25μm CMOS products.

Keywords: metrology, critical dimension, critical dimension control, optical metrology, lithography, lithography control

The CD control problem

The principal purpose of in-line CD control is to maintain a predetermined operating point for the lithography and etch patterning process at each level. Added to its obvious yield and reliability relevance is its impact on transistor performance at the gate level. Transistor speed, directly dependent on gate dimension, is a key factor in determining microprocessor market value. The price of nominally identical microprocessors can differ by hundreds of dollars due to gate dimension variation within the normal manufacturing distribution. Given the industry roadmap for gate tolerance [1], and assuming a $100 price difference between a +/- 1σ variation in gate dimension, the exponential rise in value of each nanometer, as nominal gate dimensions shrink, can be estimated as shown in Fig. 1. Under these assumptions, the value of CD control for the 180nm generation of microprocessors exceeds $10 per nanometer.

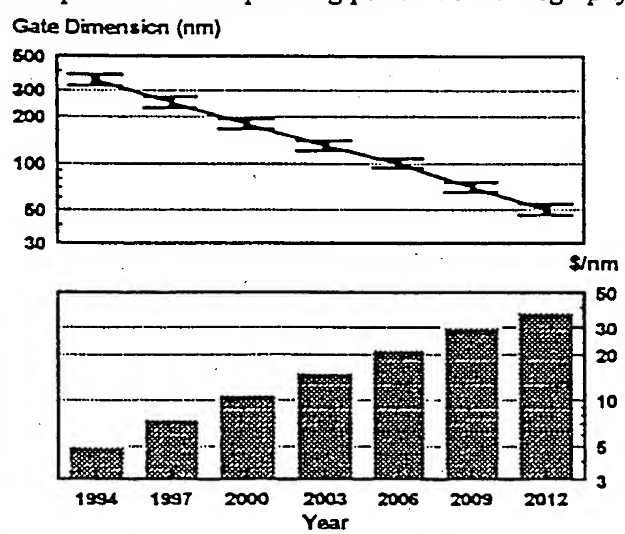

Fig.1: Estimated value of gate level CD control

While the value of CD control may be rising exponentially, so is its cost. The dominant cost is the

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improved lithography and etch capability to achieve the required patterning resolution and control. Not insignificant, however, is the cost of in-line CD metrology. Dynamic control systems based on in-situ sensors are unlikely to reduce the need for in-line dimensional measurement. On the contrary, the increasing number of pattern levels on advanced Logic and DRAM products, more complex lithography and etch processes, and the need to maintain tighter CD tolerances all drive a rising demand for CD metrology that outstrips the capability of available metrology techniques.

In pursuit of in-line measurement accuracy, the current industry strategy is to implement high-resolution tools [2]. Most prominent among these is the top-down scanning electron microscope (SEM). Despite the increasing sophistication of SEMs, in-line CD measurement accuracy has proved elusive. The exact relationship between the top-down SEM image and three-dimensional patterns on the wafer is unknown and, in all likelihood, unknowable over the range of conditions encountered in semiconductor manufacturing. Nonetheless, the SEM attempts accuracy by interpreting an average intensity profile over a segment of the top-down image. At best, the SEM algorithms are accurate to tens of nanometers – a substantial fraction, if not all, of current critical dimension tolerance. Furthermore, the pursuit of resolution often comes at the expense of precision, sensitivity, stability and speed – the characteristics most essential to effective CD control.

Optical critical dimension (OCD) metrology

To establish and maintain a desired operating point for the patterning process, CD metrology must track the relative position of any pair of edges as a function of process variation about that operating point. The high-resolution approach assumes that a minimum dimension must be measured to achieve adequate sensitivity to process variation. We base our low-resolution approach [3] on two observations: 1) the edge of an array of minimum dimension patterns is at least as sensitive to process variation as the edge of an individual pattern, and 2) the length of a two-dimensional pattern is usually more sensitive to process variation than its minimum dimension width. Several precedents validate this approach. The Murray dagger, in use since the early 1980's as a human-readable process monitor, is an example of a feature whose length is more sensitive to process variation than its width [4]. Arrays whose asymmetry is an indicator of process variation [5], as well as those consisting of Murray-dagger-like elements [6] have been applied to stepper setup. Electrical measurement of arrays has also been used to monitor contact dimensions [7]. Thus, processes which produce arbitrarily small patterns can be controlled by measuring arbitrarily large arrays. Practical implementation of array metrology dictates that we rely on optically measurable array targets to establish optical critical dimension (OCD) metrology.

In conventional optical microscopy, the degradation of resolution as dimensions approach the wavelength of light precludes its application to the measurement of individual pattern features at advanced ground rules. The blurred images of adjacent edges overlap and interfere, and the behavior of the image through changes in the process no longer bears a consistent relationship to that of the actual feature. It is this loss of measurement "consistency" that has established the practical limit of conventional optical microscopy in the

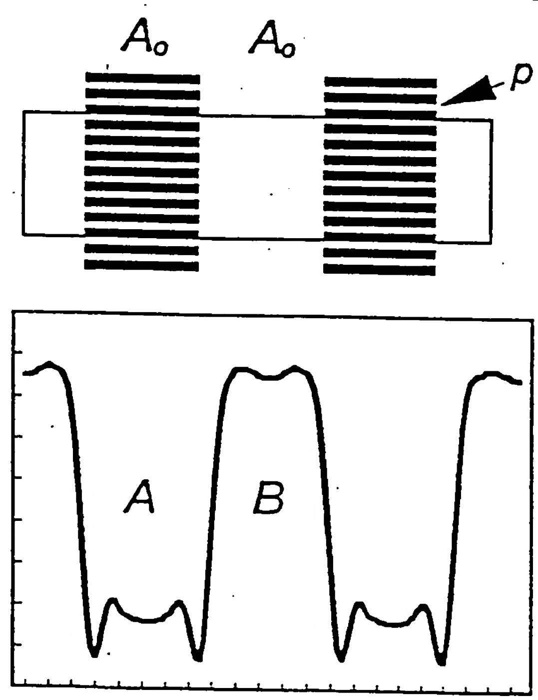

Fig. 2: Schnitzl arrays of minimum dimension elements and an associated optical intensity trace.

range of 0.5 - 1.0μm. In our application; however, provided the array dimensions we measure are significantly greater than 1.0μm, optical metrology is an attractive candidate, recommended most by the fact that the fundamental capability required already exists on overlay measurement tools. These tools can be adapted to the OCD task, where the CD is an array dimension rather than the minimum dimension. Thus, we can return to the practice of performing in-line overlay and OCD metrology on one tool, realizing significant manufacturing efficiency and cost savings.

The basis of OCD metrology is shown schematically in Fig. 2. The OCD target (a.k.a., schnitzl) consists of one or more arrays of parallel lines at a pitch p. The pitch is matched to the minimum pitch in the chip design for a specific masking layer. Using conventional optical microscopy, the image of the array(s) is brought into focus and captured on a CCD camera. An average intensity trace is collected along a length of the array(s) defined by the rectangular measurement gate in the camera's field of view. Edge detection can be conducted by a variety of techniques to determine the measured width of the array, A. As noted above, it is most important that the measured width vary consistently with the actual width over a range of process conditions about the nominal operating point.

As long as the nominal array width, A_o, is large compared to the optical resolution; namely,

$$A_o \gg \lambda/(NA(1+s)) \qquad (1)$$

where λ is the wavelength, NA is the numerical aperture, and s is the partial coherence, the array edges perpendicular to the pattern pitch will be well resolved. For the particular schnitzl layout shown, A_o also corresponds to the length of the individual pattern elements. A consequence of the minimum pitch being perpendicular to the measurement direction, is that we monitor the length of minimum dimension patterns rather than their width. Line lengths tend to be significantly more sensitive to process conditions than line widths as the resolution limit of a lithography process is approached. An added benefit to having the target pitch perpendicular to the measurement direction is that it obviates keeping the pitch below the optical microscope resolution. The result of partially or even fully resolving the pattern elements is that the pixels along the edge of the array see a modulation in the edge position. On average over a long length of the array, however, this still results in a single edge position sensitive primarily to the length of the individual lines. An example of a schnitzl tailored to the trench level of a 1Gb DRAM (2.5μm long trenches on a 0.35μm pitch) is shown in Fig 3 at both the low magnification of an optical metrology system and the high magnification of a top-down SEM.

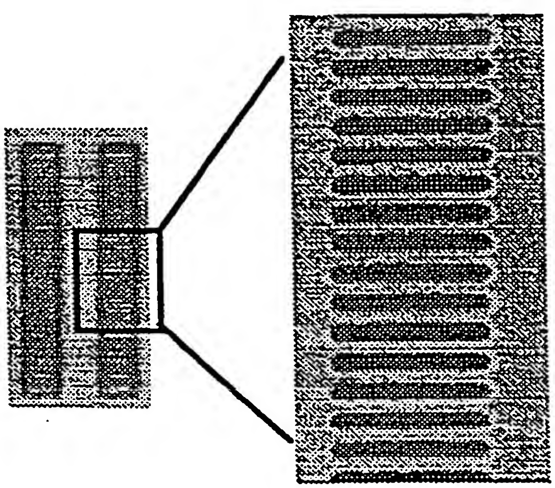

Fig. 3: 0.175μm generation trench level schnitzl: (a) low-magnification optical metrology view, (b) high magnification SEM view.

As shown in Fig. 2 and 3, we usually employ a pair of identical arrays spaced an array distance, A_o, apart. This allows us to define OCD as a bias:

$$OCD = (A - B)/2, \qquad (2)$$

where B is the measured separation between arrays. Associated with OCD is the process invariant optical half-pitch (OHP):

$$OHP = (A + B)/2 = A_o + \varepsilon \qquad (3)$$

where ε is the measurement error. Defining OCD as a bias has the advantage of self-normalizing measurements among different product levels and target designs. The associated OHP enables in-situ monitoring of the measurement precision when A and B are determined by independent measurements.

Precision

Precision and sensitivity are the measurement attributes important to the maintenance of a process operating point. Precision is the repeatability with which a fixed dimension can be measured. Sensitivity, discussed in the next section, is the response of the measured quantity to process variation of interest (process signal) and its lack of response to variation not of interest (process noise).

In the presence of gaussian noise, precision is defined as the standard deviation, σ, of a repeated measurement. For threshold detection, the σ of an edge measurement is related to the metrology system response by Bobroff's expression [7]:

$$\sigma \propto R/(\mathrm{SNR}\sqrt{n}) \qquad (4)$$

where R is the resolution, SNR is the signal-to-noise ratio, and n is the number of pixels spanning the imaged edge. Improved resolution only improves precision if the signal-to-noise ratio can be sustained. The weakness of high-resolution approaches to CD control is that resolution usually comes at the expense of an off-setting decrease in SNR. This is apparent in the case of SEM metrology, where noise contributors include both process noise (pattern edge roughness, sidewall angle, etc.) and measurement noise (charging, focus, stigmation, etc.) all of which increase with resolution. Conversely, the high SNR of optical tools enables them to achieve precision comparable or superior to top-down SEMs despite their relatively low resolution.

The results of an simple experiment conducted to determine OCD precision on one of our 0.2um ground rule product levels, under metrology conditions: threshold = 50%, R = 0.6μm, SNR = 300, and pixel size = 0.1μm, are shown in Table I. The experiment consisted of performing 50 repetitions of the A and B measurements on a schnitzl. Each repetition was measured independently by performing a separate focus, image acquisition and measurement step; however, each pair of measurements were collected in a single scan of the image. This measurement strategy enabled us to analyze the data in two ways: 1) the standard deviation of OCD and OHP were calculated for the data as collected, where they were not independent measurements, and 2) the OCD and OHP standard deviations were calculated after the A and B pairings were uniformly randomized to simulate an experiment in which they had been independently measured.

Table I. Short-term dynamic precision

	3σ(nm)	
	OCD	OHP
Single Scan	3.3	1.5
Random	2.5	2.6

Single scan results show an OCD precision of 3σ = 3.3nm and OHP precision roughly half that. When we randomize the A and B pairings, the OCD precision improves and OHP precison degrades such that they become roughly equal. It makes sense that the OCD and OHP precision should be equal in this case, since they are both derived from random pairings of the same randomly distributed numbers. The improvement in OCD precision with randomization is explained by the fact that, in the single scan case, the OCD precision was the result of a single measurement, whereas, in the randomly paired case, the OCD precision is the result of two independent measurements. For gaussian distributions a $\sqrt{2}$ improvement in OCD precision is to be expected. The degradation of OHP precision with randomization is explained by the fact that the single scan OHP does not contain the contribution of threshold noise between A and B, since they are derived from the same intensity trace.

The OHP results of our short-term dynamic precision test validate that the OHP is a good monitor of metrology precision capability provided A and B are measured independently. We will use this to assess long-term dynamic precision on product in a later section. The results also confirm that, as predicted by Equation (4), the

achievable OCD precision is adequate for metrology on our most advanced products. Furthermore, the conditions of our test suggest that there is opportunity to improve OCD precision. Improved precision can be achieved via resolution (shorter λ, higher NA), tool/target optimization to maximize SNR across product levels, increasing pixel density to increase n at a given image resolution and magnification, and more sophisticated edge detection techniques.

Process sensitivity

To amplify its sensitivity to process variation of interest, the schnitzl design in Figs. 2 and 3 exploits the image shortening response to dose and focus, the principal lithographic drivers of CD variation. As the elements of the schnitzl array approach the lithographic limit, the rate of change of the OCD increases relative to that of the minimum chip dimension. Line and space schnitzls move opposite one another through dose but in the same direction (decreasing OCD) with defocus.

An example of the OCD response relative to that of the chip dimension (trench width), measured on a top-down SEM, at the trench level of the 256Mb DRAM process is shown in Fig. 4. The schnitzl array consists of 2.5μm long trenches on a 0.55μm pitch matching the minimum pitch of the chip design. When plotted on the same scale (an offset was added to the OCD data to match the SEM value at nominal dose and focus), the OCD response to deviation from nominal is much more pronounced than the relatively flat response of the trench width. Slices of the surfaces through dose at best focus, Fig. 5, and through focus at best dose, Fig. 6, give a more quantitative picture of the relative sensitivity. The dose slope has increased by nearly a factor of two. The position of best focus and depth-of-focus is clearly indicated by the OCD focus response, whereas it is impossible to determine either from the SEM measurements of the chip feature.

Compared to its well-behaved response to dose and focus variation, OCD sensitivity to film thickness variation is more problematic. On one hand, optical metrology provides a means of monitoring thickness variation via changes in substrate reflectivity in the measurement wavelength band. On the other hand, it is possible for the reflectivity change to influence the OCD measurement. Significant shifts in reflectivity are likely to require recalibration of the OCD target to the chip dimension of interest. Reflectivity variations need to be kept within acceptable bounds to preclude false OCD readings. Film thickness control on product is not necessarily consistent with this requirement. Our experience to date, however, indicates that the OCD response to film thickness change on product can be managed. We have successfully qualified and implemented OCD control at the develop

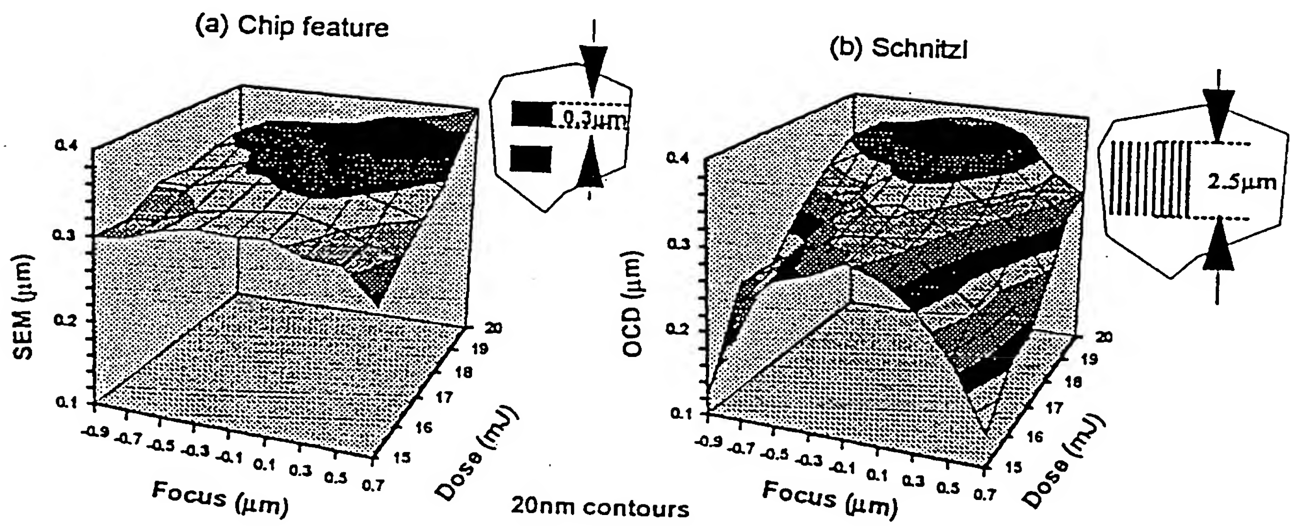

Fig. 4: Focus-exposure response surface for (a) 0.3μm trench width (b) 0.55μm pitch, 2.5μm wide schnitzl.

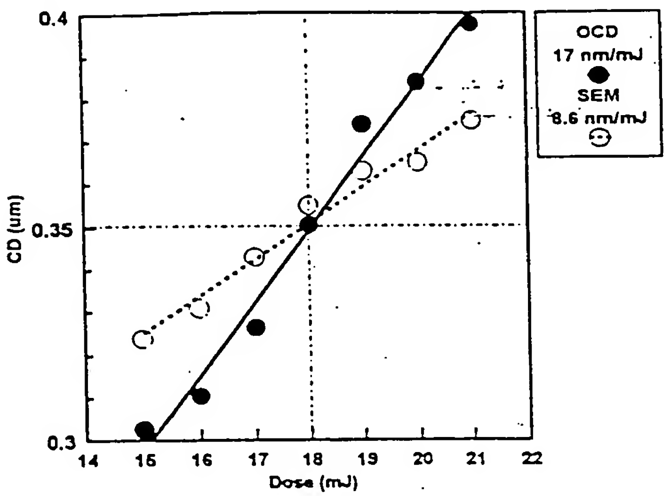

Fig. 5: Dose response at best focus.

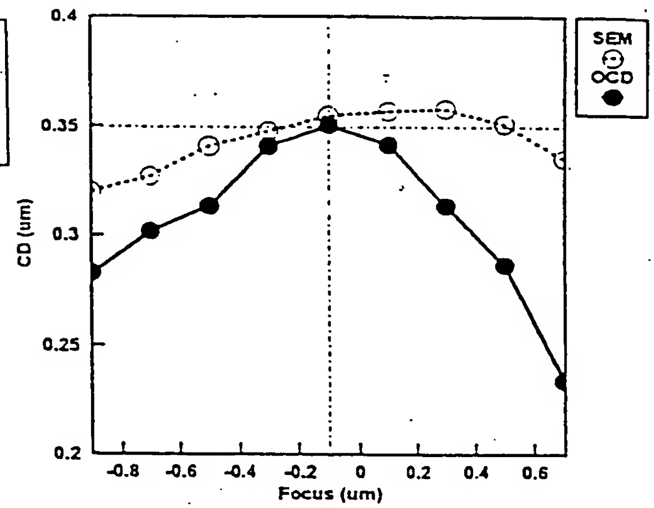

Fig. 6: Focus response at best dose.

measurement steps on several 256Mb DRAM levels, including the trench level characterized in Figs. 4-6. Our approach is best exemplified by our most ambitious product implementation to date – the application of OCD to 0.2μm gate control.

0.2μm gate control

Gate dimension control is the most critical application of CD metrology. A low-magification view of an SRAM array, as well as high-magnification post-develop and post-etch views of its gate feature (0.2μm post-etch) are shown in Fig. 7. OCD metrology was implemented in parallel with SEM metrology at the start of product runs. The SEM sampled 5 sites/wafer, 2 wafers/lot, with an average cycle-time, including queue-time, of approximately 60 minutes/lot. The OCD measurements were added to the overlay recipes, sampling a schnitzl

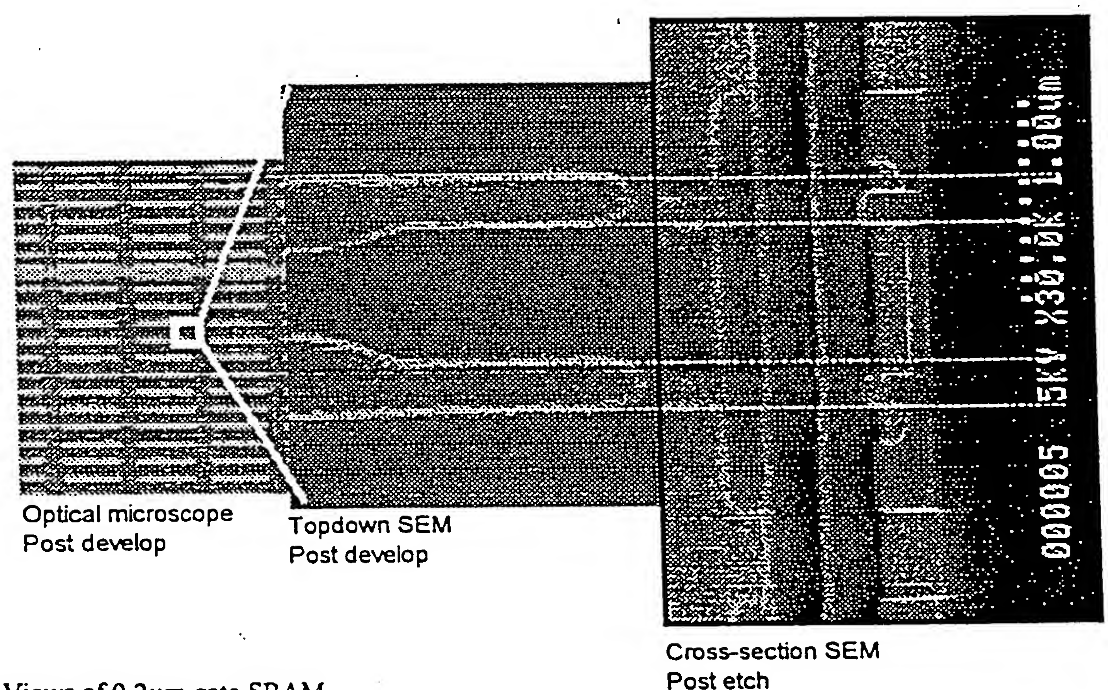

Fig. 7: Views of 0.2μm gate SRAM.

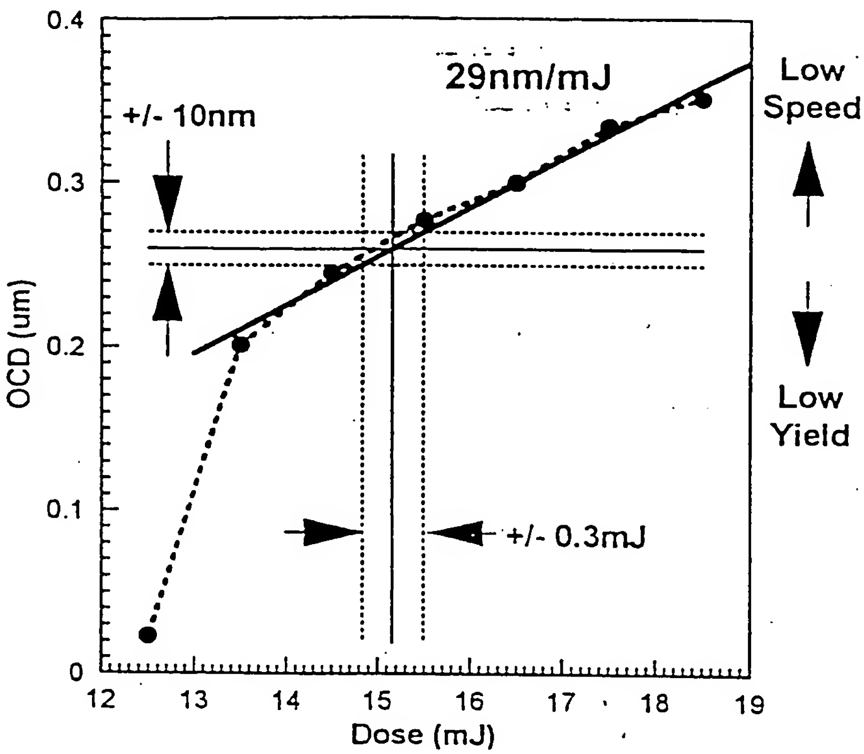

Fig. 8: Post-develop dose calibration curve for SRAM gate.

target on the same 5 chips/wafer as the SEM. but 3 wafers/lot. Since the OCD measurements were incremental to required overlay metrology. the added cycle-time was less than 5minutes/lot.

The motivation to migrate post-develop CD metrology from SEM to OCD came from a comparison of the results of the two measurement techniques on the initial twenty-five product lots. The post-etch SEM measurements of the gate dimensions showed reasonable correlation to the effective gate length at electrical test: however, the post-develop OCD measurements showed better correlation (R-squared = 0.7) than the post-develop SEM measurements (R-squared = 0.4) to the post-etch SEM data. By this measure post-develop OCD metrology was judged to enable improved process control.

The next step toward OCD implementation was to calibrate the OCD data to the 0.26μm nominal post-develop gate dimension corresponding to the desired transister clock frequency. Appropriate offsets were applied to two optical metrology tools to match them to the gate dimension and to each other (their offsets differed by 7nm). To set appropriate dispositioning and control limits, the OCD dose response was determined as shown in Fig 8. Since negative resist was used at this level. the OCD dimension increases with increasing dose, with a slope of 29nm/mJ over much of the dose range. As in the trench case above, the OCD dose sensitivity is approximately twice that of the gate dimension. At the start of processing, the nominal dose was approximately 15mJ/cm². As is apparent in Fig. 8, the OCD drops precipitously in the low dose regime, at an image size where the photoresist begins to lift. At dimensions significantly larger than nominal (on the high dose side), transistor speed would decrease. Thus, it was necessary to control the process via dose to a narrow CD regime between small gate yield roll-off and large gate speed roll-off. The allowed mean variation of the gate dimension was +/-15nm. Despite the 2x dose sensitivity amplification of OCD, we set our OCD mean limits at +/-15nm. Assuming dose variation to be the dominant contributor. we were actually controlling the develop gate dimension to +/-7.5nm.

Fig. 9 shows the OCD mean variation and corresponding stepper dose for 76 lots starting at the point at which calibration was complete. Over the course of the product run shown, the lots divided roughly equally between the two calibrated optical metrology tools. Other than routine overlay maintenance. no adjustment to either tool was made during the run, which spanned several months. OCD-based stepper dose corrections were performed manually for the first set of lots, but starting at lot 23 we initiated automated feedback control of the dose based on a three-lot rolling average of the OCD lot means and the predetermined dose response of Fig. 8. At around lot 40, an instability of the mean caused significant variation in the dose. The dynamic dose control was able to keep the three-lot rolling average of the OCD within the 15nm control limits until the mean OCD equilibrated with a downward drift of the dose after lot 60. The dose decrease was accentuated by a 3nm adjustment to the OCD target at lot 67 to fine tune the processor speed. It is noteworthy that the onset of mean OCD instability at lot 40 and its

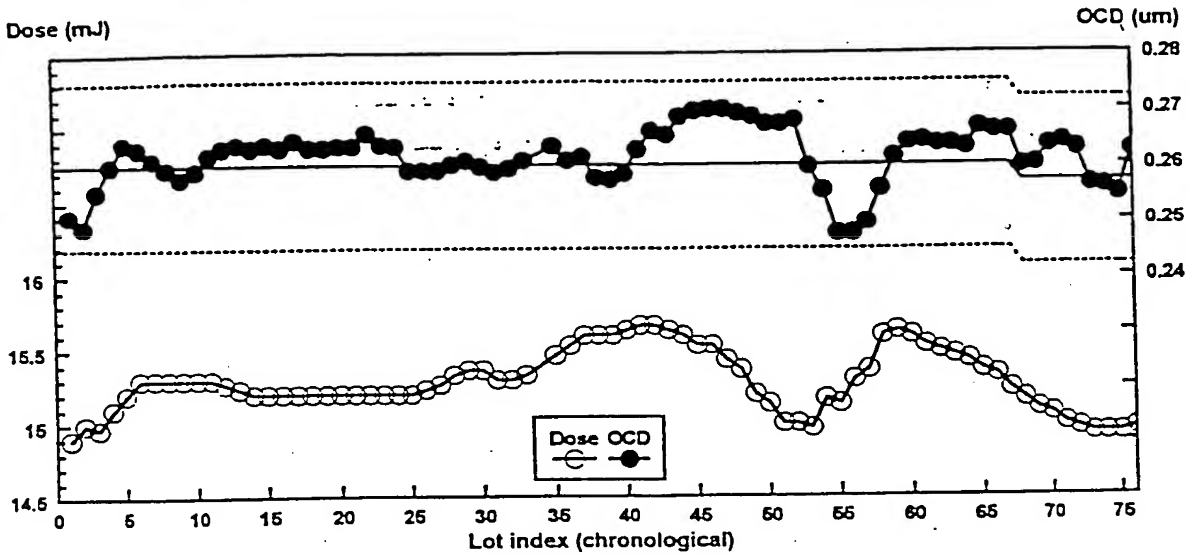

Fig. 9: Gate level mean and associated stepper dose trend (3 lot rolling average).

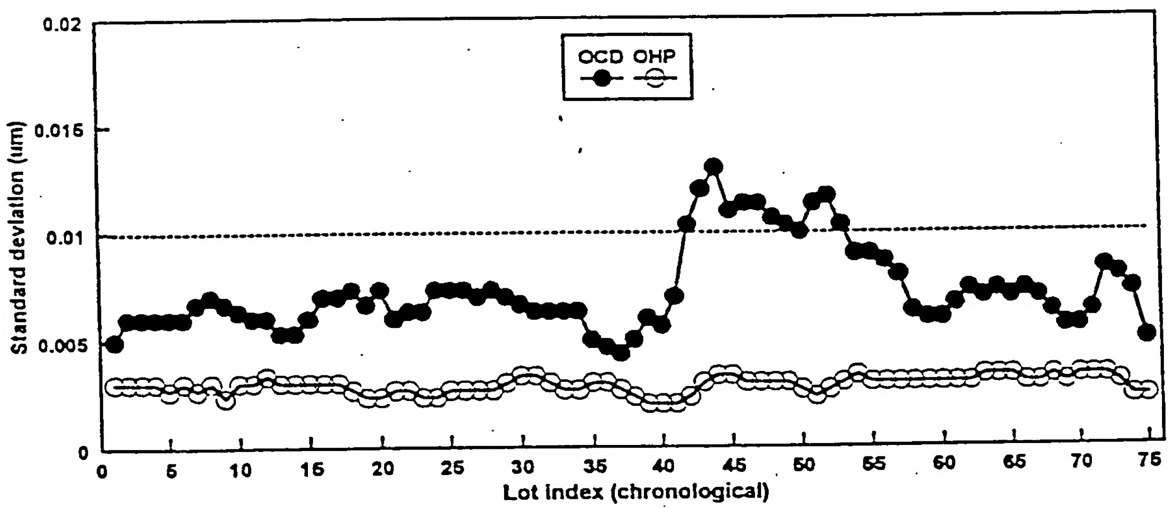

Fig.10: Gate level OCD and OHP within lot standard deviation trend (3 lot rolling average).

subsequent return to relative stability after lot 60, corresponds to a region of abnormally high OCD within-lot standard deviation as shown in Fig. 10. Throughout the run, however, the OHP standard deviation remains flat at approximately 3nm. In fact, the all-points 3σ of the OHP distribution (>1000 points) was below 10nm. Since the A and B measurements that comprise the OHP were performed independently throughout, this confirms the metrology tool stability and overall dynamic precision, including all process variation.

Since the implementation of OCD control, no send-ahead wafers have been run, insignificant gate-level rework and no scrap has been incurred for critical dimension in-line spec violation. More importantly, the Logic product on these lots has exceeded all yield and speed sort requirements.

Summary

We have developed an optical method of critical dimension metrology (OCD) whose improved precision, sensitivity, stability, speed and extendability relative to high-resolution alternatives make it an attractive CD

metrology candidate. We are engaged in an ongoing effort to understand ana enhance its performance, principally in the area of tool/target optimization. Nonetheless, OCD has already proven its technical and economic worth. While our paper has focused on in-line product control, we have also utilized OCD as a lithography setup, characterization and diagnostic tool. Given its demonstrated ability to capture focus-exposure response, we are applying OCD to process window optimization and monitoring. Furthermore, we have reinvested some of the time savings that OCD affords in increased product sampling to partition systematic components of CD variation, providing much needed inisight into on-product process dynamics.

Our OCD results suggest a change to the industry's exclusively high-resolution approach to CD metrology. OCD can bear the brunt of in-line product monitoring requirements, where the viability of relatively slow high-resolution tools is most in question, as well as a sizable fraction of the lithography and etch characterization role. A variety of metrology techniques remain essential for the characterization, calibration, inspection and diagnostic tasks that require within-chip measurement or visual confirmation of minimum dimension patterns. With an appropriate mix of OCD and high-resolution tooling, tailored to the diverse demands placed on CD metrology, the CD control requirements of the semiconductor industry can be met for the foreseeable future.

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